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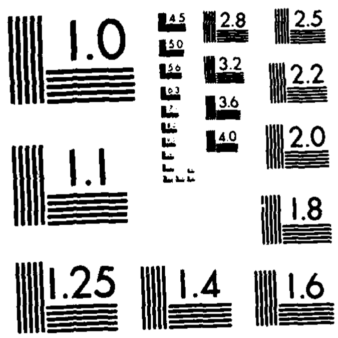

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COMMENTS ON "BOUNDED ERROR ADAPTIVE CONTROL"*

by

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ABSTRACT

The purpose of this note is to discuss the model matching performance of the adaptive control algorithm suggested by Peterson and Narendra in ~~reference [1]~~. 'Bounded Error Adaptive Control'.

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INTRODUCTION

Following the excitement over the global stability properties of model reference adaptive control (MRAC) algorithms, during the past two years several researchers, [1] to [5], have been investigating the robustness of MRAC algorithms to unmodeled and unmeasurable disturbances and/or unmodeled high-frequency dynamics. It is now widely appreciated that standard MRAC algorithms can become untable if there exist persitent errors (which may be induced by persistent disturbances). The presence of persistent errors, coupled with the adaptive gain mechanism of MRAC algorithms, cause "drifts" in the adaptive gain parameters, which in turn increase the control bandwidth thereby exciting the unmodeled high frequency dynamics and resulting in an unstable control system.

The research of Peterson and Narendra [1] deals with the problem of minimizing the effect of unmeasurable disturbances upon the drift of the adaptive gain parameters; it does not deal with the presence of the inevitable unmodeled dynamics. The basic idea in [1] is to introduce a dead zone nonlinearity in the output error channel, so that small errors due to the disturbances will not "confuse" the adaptive control gain setting mechanism. This is certainly a good idea; Peterson and Narendra [1] present the necessary analysis to establish the boundedness of all signals in the adaptive control loop, and infer stability.

The purpose of this note is to examine issues of performance of the resulting adaptive control system using the simulation results presented in Section IV, Fig. 6 by Peterson and Narendra [1]. The published simulation results confirm the claim that the inclusion of the dead-zone leads to bounded steady-state control gains in the presence

of disturbances while in the absence of the dead-zone the control gain parameters could drift (see Fig. 6(a) in [1]).

However, the performance of the bounded error adaptive control scheme has yet to be evaluated. There are many ways by which one could examine the performance of an adaptive control system, and there does not seem to be any agreement on their rank-ordering and performance. In this note we study a particular measure of performance, namely the ability of the adaptive control scheme to "match" the dynamics of the model transfer function once control parameter convergence has taken place. We believe that this is a relevant and meaningful measure of performance; after all historical MRAC algorithms had the same objective: to match the transfer function of a given dynamic model.

NUMERICAL STUDIES

The numerical results of Peterson and Narendra [1] assume that the model transfer function is

$$W_m(s) = \frac{1}{s^2+4s+3} = \frac{1}{(s+1)(s+3)} \tag{1}$$

The plant to be controlled has the open-loop transfer function

$$W_p(s) = \frac{1}{s^2-1} = \frac{1}{(s+1)(s-1)} \tag{2}$$

Figure 1 (not included in [1]) shows the structure of the adaptive control system. The structure of Fig. 1 can be deduced from the general equations given in [1]; the three adaptive control gains θ_1, θ_2 and θ_3 form the parameter vector $\underline{\theta}^T \triangleq [\theta_1 \theta_2 \theta_3]^T$ and are adjusted on the basis of the signal $\eta(t)$ at the dead zone output. When adaptation has proceeded to the point when the magnitude of $\varepsilon(t)$ is upper bounded by the dead zone cutoff $\nu_o+\delta$, we have $\eta(t)=0$ and $\dot{\theta}(t)=0$. This results in $\bar{\varepsilon}(t)=0$ and leaves the compensated plant transfer function as

$$\frac{y_p(s)}{r(s)} = \frac{s+2}{s^3+(2-\theta_1)s^2-(1+\theta_3)s+\theta_1-\theta_2-2\theta_3-2} \qquad (3)$$

Straightforward algebra confirms that the vector of parameters giving correct model matching (in the absence of the disturbance v_1) is

$$\underline{\theta}^{*T} = [-4,12,-12]^T \qquad (4)$$

Using Eq. (4), the compensated plant transfer function (3) reduces to

$$\frac{y_p(s)}{r(s)} = W_m(s) = \frac{(s+2)}{(s+2)(s+1)(s+3)} = \frac{1}{(s+1)(s+3)} \qquad (5)$$

Next we compare the correct $\underline{\theta}^*$ with the steady state $\underline{\theta}_{ss}$ parameter vectors shown in the simulation figures 6c,d,e of [1].

From figure 6c of [1] we have

$$\underline{\theta}_{ss} = [-0.2,-8.0,-12.2]^T \qquad (6)$$

and therefore the adaptation has converged to the transfer function

$$\frac{y_p(s)}{r(s)} = \frac{s+2}{(s+2.52)(s-.16+j3.46)(s-.16-j3.46)} \qquad (7)$$

which has two lightly damped poles in the right half plane. The results in figure 6d of [1] yield

$$\underline{\theta}_{ss} = [-2.1,-9.2,-12.3]^T \qquad (8)$$

which corresponds to the transfer function

$$\frac{y_p(s)}{r(s)} = \frac{s+2}{(s+3.36)(s+.37+j2.95)(s+.37-j2.95)} \qquad (9)$$

The results of figure 6e in [1] yield

$$\underline{\theta}_{ss} = [-0.6,-10.2,-17.0]^T \tag{10}$$

which corresponds to the transfer function

$$\frac{y_p(s)}{r(s)} = \frac{s+2}{(s+2.6)(s+j4)(s-j4)} \tag{11}$$

We would expect the results depicted in figure 6e to be "best" in the sense of model matching since this simulation employs the smallest dead zone and the richest input. (Unfortunately, the rich input is not defined). In all cases, however, the resultant system is very lightly damped and cannot be considered a very good approximation to the model $W_m(s)$ it seeks to match. In the case of figure 6c in particular, the compensated plant transfer function (7) is that of an unstable system. This result appears inconsistent with the error time history shown.

CONCLUDING REMARKS

We can only conclude, based on the findings reported in [1], that when viewed from the perspective of model matching performance, the results of adaptive controller design with a dead zone non-linearity in the parameter update law are presently of limited practical value. The theoretical importance of guaranteed state boundedness in the presence of persistent disturbances is a step in the right direction. This development should inspire work aimed at improved model matching in the presence of persistent disturbances as well as under conditions of imperfect model-plant structural matching due to the presence of high order unmodeled dynamics.

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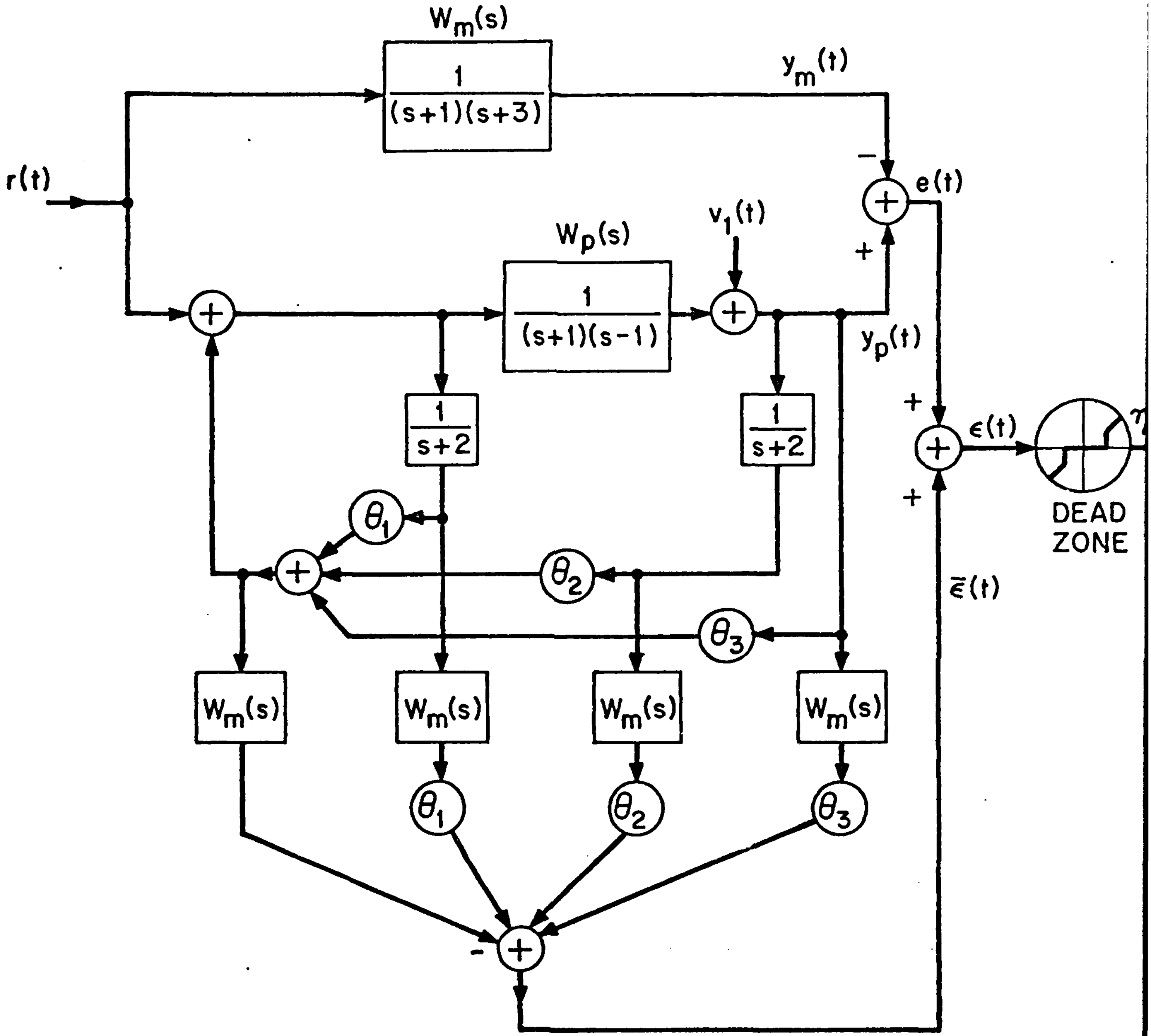

Figure 1: The structure of the adaptive control system for the numerical example presented in Ref. [1]. The adjustment mechanism for the adaptive control gains ϕ_1, ϕ_2, and ϕ_3 is not shown.

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